MEASURING RF POWER

Your transmitter's RF power output is a key indicator of its health, and here are the circuits, instruments, and techniques you can use to accurately "take its temperature."

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Radio frequency (RF) power is one of the principal performance indicators of radio transmitters. Whether you are a ham-radio operator, citizen's-band operator, or a commercial radio-communications technician, the RF-power output of your transmitters is a key indicator of its health. RF power measurements vary from a few milliwatts up to many kilowatts. In this article we will take a look at some of the principal methods for measuring RF power.

RF power measurement is no different from other alternating-current (AC) power measurements, although the increased frequencies involved cause some problems. Power is still described by the standard equations ($P = V \times I$, $P = I^2 \times R$ and $P = V^2/R$), so if you can measure the current or voltage and know the resistance, you can measure power. The problem is relatively easy with sine-wave RF, such as unkeyed continuous wave (CW) signals, but becomes a bit more complicated on modulated, chopped, keyed, or pulse RF waveforms. In any event, the most basic power level measured is the root-mean-square (rms) value, which equates the power's heating ability to a like amount of heating from a DC source. The trick is in making rms readings.

RF Ammeter Methods. The thermocouple RF ammeter (see Fig. 1) is an inherently rms-reading device because it relies on heating a very low value resistive heating element (R). The temperature of the heating element is measured by a thermocouple device (TC in Fig. 1), which produces a voltage proportional to the temperature of the thermocouple junction. A DC voltmeter is used to measure the thermocouple output, but its scale is calibrated in units of current (amperes, milliamperes).

When the RF ammeter is in series with the transmission line from the transmitter to a resistive load (R_L) or a resonant antenna, the rms RF power level can be calculated from $I^2 \times R_L$. The advantage of the thermocouple RF ammeter is that it can be used with any load resistance, while other meters are designed for a specific load (usually 50-ohms). The disadvantages include the need to make a calculation, and the fact that RF ammeters tend to fade out above some frequency in the 40- to 70-MHz range.

Calorimeter/Bolometer Methods. A number of professional-grade RF-power meters are based on the fact that the temperature change in a resistive load is proportional to the rms value of the applied RF waveform. Figure 2 shows a basic form of calorimeter or bolometer: A heat-dissipating resistor with a resistance value equal to the desired load impedance is enclosed in an assembly with some sort of temperature-measurement device.

Theoretically, you could put a big dummy load in a room and use a glass-mercury thermometer to measure the air temperature of the room before and after the power was turned on, but that's hardly practical. If, however, you embed a dummy load and some temperature sensor (thermistors and thermocouples are used) in a small assembly, then the before and after temperature rise of the resistor can be measured.

A low-cost instrument can be built using only the dummy load and Temperature Sensor 1, but that would ignore the problem that ambient temperature also affects the measurement sensor. It is not uncommon to include a second sensor to measure ambient temperature, so that changes in ambient temperature can be factored into the measurement. The results can then be displayed on an analog or digital meter.

Some calorimeter methods use two sensors (three could be used if ambient is accounted for) in a comparison measurement. A low-frequency (e.g. 60-Hz) AC power source is used to drive one sensor/resistor, while the RF power is used to drive the other. A differential

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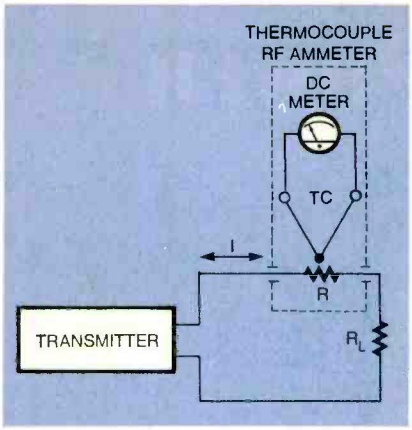

Fig. 1. The thermocouple RF ammeter relies on heating a very low value resistive heating element (R) to measure RF power.

meter will show when the two output levels are the same. At this point, the easily measured 60-Hz AC power level is equal to the applied RF power.

Simple Diode Detector Methods. A simple diode detector scheme (see Fig. 3) can be used to measure the RF power applied to a load. The scheme shown was used on the Heathkit *Cantenna* dummy load that was popular some years ago, and is still used on similar products today.

The diode is an envelope detector, and produces a pulsating DC output from the RF voltage applied across the load (R_L). Capacitor C1 filters out the pulsations to pure DC. The power can be inferred from V_o^2/R_L.

The actual voltage applied to the diode is reduced by a resistive voltage divider (R1/R2) and is only a fraction of the applied voltage. This allows higher power levels to be measured. A diode such as a germanium 1N60, a silicon 1N914 or 1N4148, or a Schottky diode can be used for D1. Note that both R1 and R2 should be much larger than the load (R_L). Typical values for the circuit are R1 = 100,000 ohms, R2 = 1000 ohms, and C1 = 0.05-µF.

The diode detector circuit of Fig. 3 remains popular because it is simple and easy to implement. But it suffers from the fact that it measures the approximate peak power, not the rms power. On a sinewave CW signal, the rms power can be approximated by $(0.707 \times V_o^2)/R_L$.

In-Line RF Wattmeters. Perhaps the most common forms of RF power meter is the in-line wattmeter (see Fig. 4). The instrument is inserted in the coaxial line between the transmitter and either the antenna or a dummy load. Instruments designed for use with an antenna often have the ability to measure the forward and reflected power, so they can also be used to determine the standing wave ratio (SWR).

The classic Wheatstone bridge can theoretically be used for making an in-line RF wattmeter, but that is not a practical approach. Such bridges are useful for making antenna impedance measurements at low power levels, but they cannot be left in-line because of the huge insertion loss involved. Other bridges, such as the micromatch bridge, discussed next, are used instead.

Micromatch Bridge. Figure 5 shows the basic capacitor-resistor micromatch-bridge circuit. Immediately we see that the micromatch is better for those applications than a conventional Wheatstone bridge because it only places a 1-ohm resistor

TABLE 1—METER READINGS BASED ON 100-WATT RMS CW CARRIER

Waveform	PEV_{rms}	$PEP(PEV^2/Z_o)$	Thermal Power
CW	100/1.414 V	100 W	100 W
AM (100%)	200/1.414 V	400 W	150 W
AM (73%)	173/1.414 V	300 W	127 W
SSB (1 tone)	100/1.414 V	100 W	100 W
SSB (2 tone)	100/1.414 V	100 W	50 W

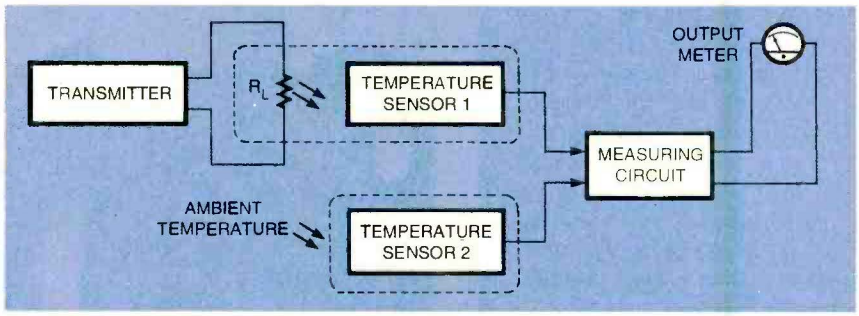

Fig. 2. In the bolometer/calorimeter approach to measuring RF power, a heat-dissipating resistor with a resistance value equal to the desired load impedance is enclosed in an assembly with some sort of temperature-measurement device. A number of commercial devices are based on this approach.

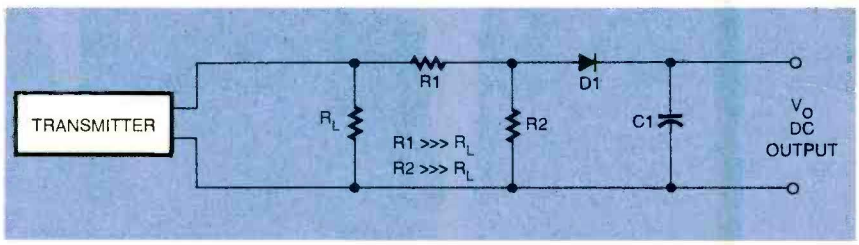

Fig. 3. A simple diode detector scheme shown here was used on the Heathkit Cantenna *dummy load that was popular some years ago, and is still used on similar products today.*

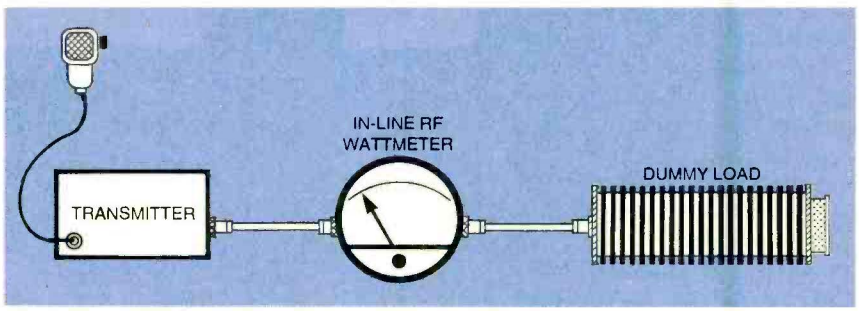

Fig. 4. Almost all RF wattmeters in use today are the in-line type.

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(R1) in series with the transmission line. That resistor dissipates considerably less power than the resistors typically used in Wheatstone bridges. Because of that low-value resistance we can leave the micromatch in the line while transmitting.

As with Wheatstone bridges, the ratio of the resistances and/or reactances in the arms must be equal to create a null output to the meter. In that case, the ratio of the capacitive reactances of C1 and C2 must match the ratio of R1 and the antenna or load resistance R_L:

$$X_{C1}/X_{C2} = R1/R_L$$

For a 50-ohm load, the ratio is 1/50, while for 75-ohm loads it is 1/75. A compromise situation that yields a small error on both 50-ohm and 75-ohm systems is to use a 68-ohm value for R_L, and make the ratio X_{C1}/X_{C2} = 1/68. These ratios occur when C2 ≈ 15 pF for 50-ohm systems, C2 ≈ 10 pF for 75-ohm systems, or C2 ≈ 12 pF for the compromise 68-ohm value.

The sensitivity control can be used to calibrate the meter. For fixed power meters, that potentiometer can be a trimmer type that is set when the meter is calibrated, and then left alone. At least one commercial micromatch bridge that was once popular with CB service technicians used a three-position switch to select three different sensitivity controls for 10-watt, 100-watt or 1000-watt power levels. Each range has its own sensitivity control, and those are used as needed.

Monomatch Bridge. The monomatch bridge of Fig. 6 is one of the "instruments of choice" for hams and other users for measuring RF power in the HF and low VHF ranges. In the monomatch design, the transmission line is segment "B", while the directional coupler transmission line segments are "A" and "B". The directional coupler lines are used for sampling the forward and reverse RF signals. Although some instruments used modified coaxial transmission lines, later versions use PC-board elements for A, B and C.

The sensor unit is basically a directional coupler with a diode detector element for both forward

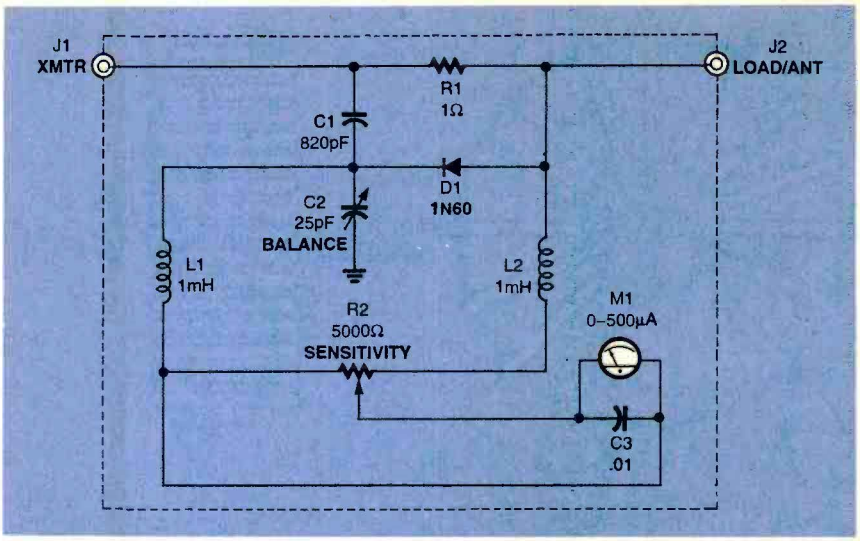

Fig. 5. The micromatch RF wattmeters offer important advantages over traditional Wheatstone bridges in RF power meter applications because they dissipate less power, allowing them to be left in the line.

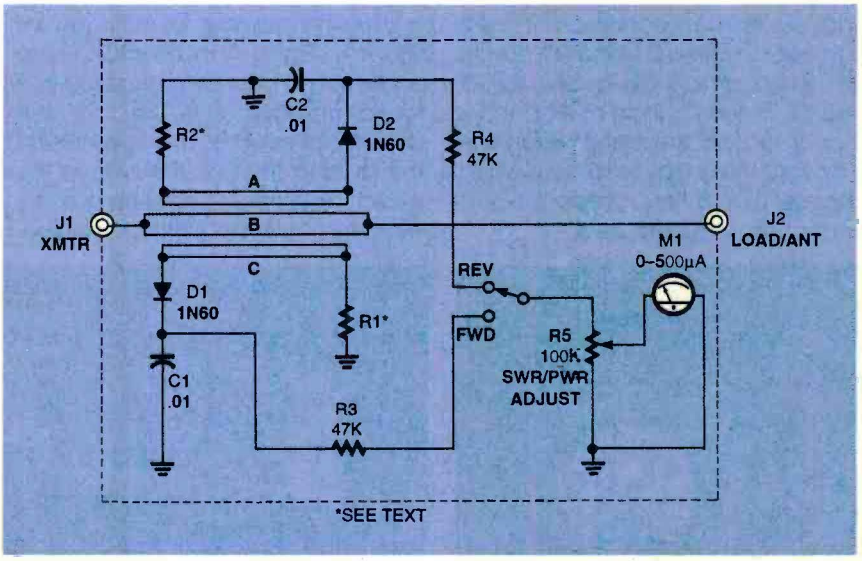

Fig. 6. The monomatch RF wattmeter is one of the "instruments of choice" for hams and other users for measuring RF power in the HF and low VHF ranges.

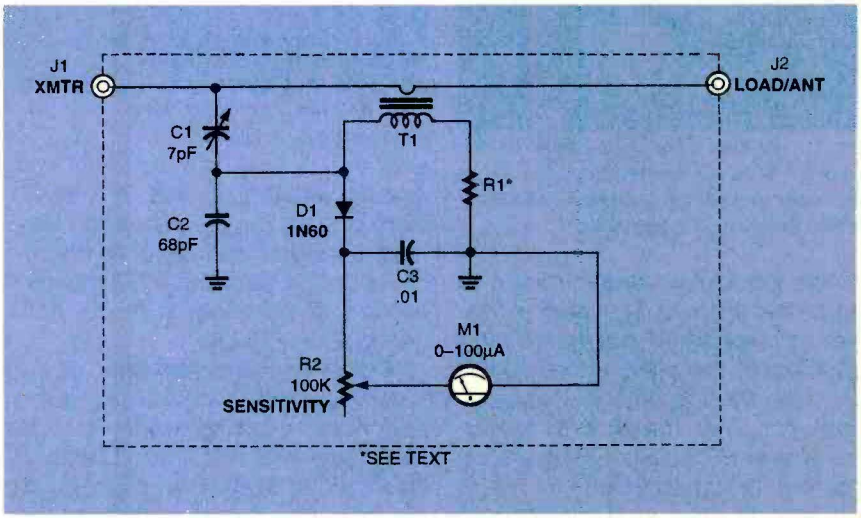

Fig. 7. In this version of the monomatch RF wattmeter, a single-turn ferrite or powdered-iron toroid transformer is used as the directional coupler.

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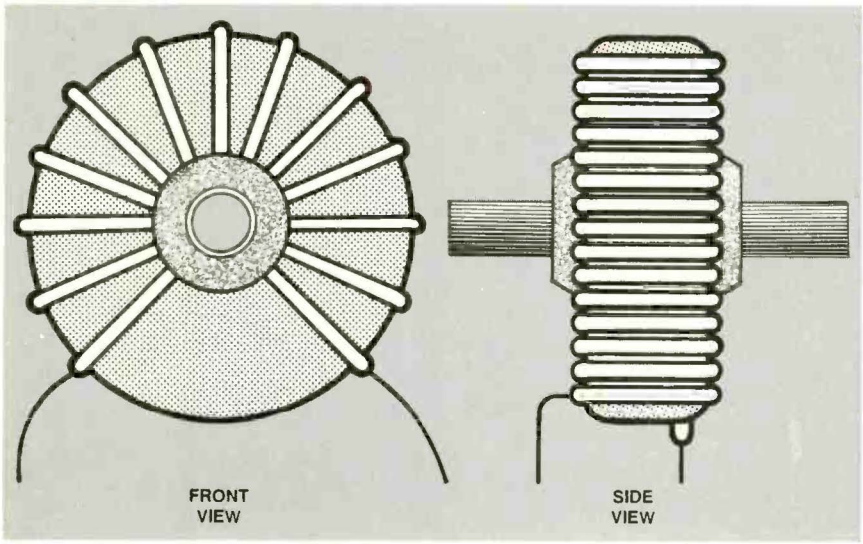

Fig. 8. Here are the winding details for the toroid transformer in the monomatch RF wattmeter in Fig. 7.

and reverse directions. For best accuracy, diodes D1 and D2 should be a matched pair, as should R1 and R2. The resistance of R1 and R2 should match the transmission-line characteristic impedance, although in many cases the 68-ohm compromise is used.

a transmission-line transformer as shown in Fig. 7. In that instrument, a single-turn ferrite or powdered-iron toroid transformer is used as the directional coupler. The transmission line passing through the hole in the toroid "doughnut" forms the primary winding of the transformer. The secondary winding consists of 10 to 20 turns of small gauge enameled wire and is connected to a measurement bridge circuit (C1, C2, plus the load) that produces a diode-rectified output voltage.

Details for the construction of the sensor assembly is shown in Fig. 8. The secondary winding, made of 24- to 30-gauge enameled wire, is wound as shown in Fig. 8, with at least a 30 degree separation between the ends to minimize distributed capacitance. A rubber grommet is inserted into the hole of the toroid. The primary winding is a single conductor passing through the hole. It is common to find $^1/_8$-, $^3/_{16}$-, or $^1/_4$-inch brass tubing used for the primary. Note: When counting turns on a toroidal transformer, each pass through the hole is a "turn," so passing a straight wire or tube through the toroid hole once counts as one turn.

The value of R1 should match the transmission-line impedance, although, as usual, the 68-ohm compromise is often seen. If you opt to use the exact value in any of those circuits, then you can use either a single 51-ohm resistor, or two 100-ohm resistors in parallel. If you can find a precision 50-ohm resistor, however, use it (in standard carbon-composition or metal-film resistors, 51 ohms is a standard value, but 50 ohms is not).

Complex Waveforms. Measuring the RF power of unkeyed CW waveforms is relatively easy, but when modulation is applied, many instruments will read incorrectly. Table 1 shows some of the factors that compare the listed waveform's power, peak envelope voltage (PEV), peak envelope power (PEP) and equivalent thermal power with a 100-watt unmodulated, unkeyed CW carrier.

Fig. 9. The Bird Electronics Model 43 RF wattmeter is an old war horse that has served the author well over the years (photo courtesy of Bird Electronics Corporation).

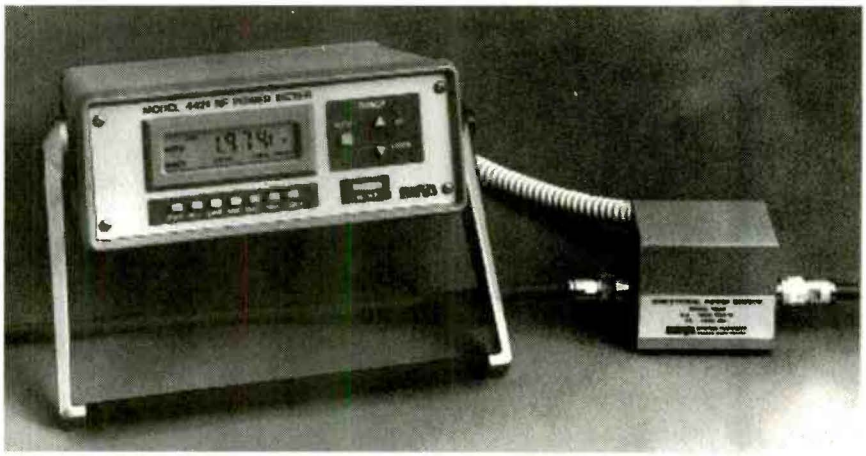

Fig. 10. Bird Electronics Model 4421 RF wattmeter (photo courtesy of Bird Electronics Corporation).

The particular version shown in Fig. 6 uses a single DC meter movement to monitor RF power. With the addition of the switch and potentiometer R5, the circuit becomes both an SWR meter and a forward/reverse RF-power meter. Many modern instruments use two meter movements, one each for forward and reverse power.

A variation on the theme uses

Some Commercial Instruments. Figure 9 shows a commercial RF power meter that the author bought nearly thirty years ago and has used heavily ever since. It is the Bird Electronics Corporation (30303 Aurora

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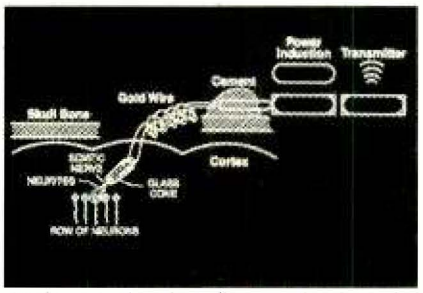
and developed using animals for **over** 12 years before it was implanted in humans. Both Federal Drug Administration and Institutional ethical approvals were obtained before the implants were made.

"The trick is teaching the patient to control the strength and pattern of the electric impulses being produced in the brain," Dr. Bakay said. "After some training, they are able to 'will' a cursor to move and then stop on a specific point on the computer screen."

First Tests. The electrodes have been successfully implanted into the brains of two patients at Emory University Hospital, one with amyotrophic lateral sclerosis (ALS or Lou Gehrig's disease) and one with a brainstem stroke. The first patient was able to control computer signals in an on/off manner for 76 days before she died from her terminal ALS condition.

The second patient, who is at the Atlanta Veterans Affairs Medical Center, is paralyzed except for his face due to a stroke and a subsequent heart attack. While dependent on a ventilator and unable to speak, he is fully alert and intelligent.



As shown in this block diagram, the electrode, which is housed in a cone-shaped glass enclosure, is implanted into the cortex of the brain and brain cells are induced to grow onto its tip. Neurons transmit an electronic signal when they "fire." Gold recording wires pick up the neural signals and transmit them through the skull. The system is powered by an induction coil placed over the scalp.

The electrodes were implanted in the part of the patient's brain that once controlled his arm and facial motion. All he has to do is think about moving his arm to create the electrical signals that are translated by the computer into movement of the cursor from icon to icon in a horizontal direction. As each icon is encountered, a phrase such as "See you later. Nice talking with you." is spoken by the computer.

The researchers are now working to help the patient communicate with the computer to produce speech, as well as provide word processing, control of his environment, and maybe even access the internet. The future includes implanting the electrode in the brains of other "locked-in" patients.

Other Applications. The brain-implant technology has other applications. For instance, it could be used as a "spinal bypass" for those with spinal cord injuries that left them with stiff and uncontrollable muscles. Here neural signals could provide some control of electrical stimulators that activate the paralyzed muscles, therefore bypassing the area of spinal-cord injury.

The technique can also be used for basic research on understanding how the brain works. Never before have recordings been made from a human brain for so long and with such stability. For example, the firings of recorded neurons may change in response to differing inputs from different body parts: If neurons fire with taps to the arm, their firing may change over time from repeated taps to the face. This will help researchers understand how the brain communicates with other parts of the body. Ω

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Road, Cleveland, OH, 44139; Tel: 1-440-248-1200) *Model 43 Thruline* meter. It's a tough old war horse! That instrument is an in-line meter that uses a plug-in directional coupler and detector element to customize the meter for different RF power levels and frequency ranges. The tip of the plug-in element comes in close proximity to the coaxial line that runs inside the meter case from connector-to-connector. The analog meter displays the value of the RF power being measured.

The case of the *Model 43* has two sockets for additional plug-in elements to accommodate other power and frequency ranges. The heavy leather case that protects the meter in transit has space for several more elements. I have elements for amateur radio HF (10 watts for QRP, 100 watts for my transceiver, and 1000 watts for my linear amplifier), amateur radio VHF (50 watts), and lower power VHF (for marine radios).

Notice in Fig. 9 that the element has an arrow on it. The arrow points in the direction of power measurement. For example, if the load is connected to the right-hand coaxial connector, and the transmitter is connected to the left-hand coaxial connector, then the meter (as shown) will measure the forward power. If the direction of the arrow is reversed, then the reflected power can be measured. Once both the forward power (P_F) and reflected power (P_R) are known, the SWR can be calculated; but to makes things easy, the Model 43 comes with a nomograph in the instruction book that makes the calculation graphically.

The Bird *APM-16* Advance Power Meter, shown at the beginning of this article, is similar in concept to the older Model 43, but is considerably advanced. While the Model 43 measures rms CW power, the APM-16 will measure analog and digital complex waveforms, as well as CW (*e.g.* CDMA, TDMA, FDMA, COFDM and other modulation). It will measure both peak and rms power levels.

Figure 10 shows a Bird meter that uses a different approach. That meter uses a remote sensor head connected in-line between the source and load, and a multi-range digital readout display.

That wraps up our look at RF power-measurement circuits and instruments. Whether you need to measure RF power as part of your hobby or for your profession, keep the concepts we've discussed here in mind and you won't go wrong. Ω

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